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THE PHYSICS OF VERY HOT PLASMA

L. A. Artsimovich

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Academician L. A. Artsimovich

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Plasma -- Fourth State of Matter

Plasma physics is not numbered among the main lines of present-day science. It is, rather, a kind of outlying street, lately made over from a desolate alley. Practically speaking, it has had two births: the first investigations relating to plasma physics appeared at the beginning of this century, and plasma physics then had a rebirth in about the fifties owing to the emergence of the idea of controlled thermonuclear synthesis. The several intervening decades between the two periods of development were years when this problem languished in practically complete oblivion and plasma physics was indeed a most desolate byway.

A characteristic feature of plasma physics is that the principal incentives for its development in both the first and the second phase were its practical applications, understood in the broadest sense of the word. This applies especially to the present-day period when the greatest interest focuses on the physics of high-temperature plasma, which in its turn is closely linked with the problem of controlled thermonuclear synthesis [See Note]. Moreover, plasma physics has taken on new significance just now because it has become the scientific foundation of the magnetohydrodynamic method for transforming thermal energy into electric energy.

[Note]: See Priroda (Nature), 1957, No. 1, pp 18-25.

During the first atage of development plasma was of interest to physicists primarily as a very unique conductor of electric current and, at the same time, as a source of light. It was with these properties of plasma that its practical applications in gas-discharge technology and illumination engineering were connected.

At present we see plasma in a completely different light. It is a new high-temperature state of matter and, in addition, a kind of dynamic system. Plasma interests us to a greater extent as an object acted upon by magnetic forces.

This aspect of the dynamics of plasma is making a definite imprint on all contemporary formulation of research in this domain, and it is this aspect which in fact is used not only in solving the problem of controlled thermonuclear synthesis, but also in the magnetohydrodynamic method of energy conversion.

Cold and Hot Plasma

This article is devoted to only a few problems in the physics of very hot plasma. Let us start off with a comparative characterization, on the one hand, of the cold plasma used in the technology of gas-discharge devices and, on the other, the high-temperature plasma which we are endeavoring to produce in connection with the problem of controlled synthesis.

Plasma is characterized by the following fundamental parameters: electron concentration; electronic temperature T_e; ionic temperature T_i; and coefficient α which determines the degree of ionization, i. e. the ratio of the number of charged particles to the total number of particles in the system.

When we talk about cold gas-discharge plasma, the value of α in this case is small in comparison with one. The value of T_e is of the order of 10^4 degrees (converted into electronvolts, this is of the order of one electronvolt), and ionic temperature is significantly lower than electronic temperature.

This is a rough characterization of the fundamental parameters of the ordinary cold plasma which we have so far encountered. The plasma which is needed for the thermonuclear generators of the future has quite different properties.

In the first place, it must be totally ionized; coefficient α is practically equal to one. In the second place, electronic and ionic temperature must be approximately of the order of 10^8-10^9 degrees, which corresponds to average particle energy of the order of tens of electronvolts. We must indeed produce this state of matter in order to solve the problem of controlled thermonuclear synthesis. It is towards this goal that all our efforts are concentrated at the present time.

Theory and Experiment

Essentially, the fundamental problem in the physics of high-temperature plasma is simply to create the very object of investigation. This problem of obtaining a new state of matter can be studied in a "two-dimensional" aspect, i. e. when plasma is described by equations laid down on paper, and in a "three-dimensional" aspect when we are obliged concretely to produce this new state of matter. In contrast to the first aspect, under which investigations have advanced very far and the theory of high-temperature plasma has attained very important results, experimental investigations are still in only the very initial stage -- for the present there is no way for them to catch up with theory.

This disproportion is characteristic of present-day plasma physics. But nonetheless we must begin our exposition precisely with an analysis of the "two-dimensional" aspect, i. e. the results of theoretical research on plasma, because the very first theoretical conclusions have served as the starting point for the development of the main directions in experimentation.

The Interaction of Particles in Plasma

High-temperature plasma can be regarded as a mixture of two ideal gases. Electrons serve as one component, ions as the other. For simplicity we shall consider that we are dealing with hydrogen plasma. This assumption has no significant influence on the results.

The concentrations of ions and electrons in high-temperature plasma have to satisfy the condition of quasi-neutrality. This condition means that space charges are mutually compensated.

Thus, we are dealing with two ideal gases present in different quantities. From a theoretical point of view this is, in a certain sense of the word, the simplest case of a system with collective interaction of particles. They are Coulomb interactions of individual charged particles among themselves, which can approximately be described as "Coulomb collisions."

Of course, Coulomb interaction of particles in plasma leaves a definite imprint on the general properties of such a gas. If we want (and this is often necessary, at least in the analysis of experiments) to investigate such phenomena as free mean path, effective cross section, and mean time between collisions, we must take into account the specific properties of the process. In contrast to the elementary picture where we consider that each particle moves rectilinearly and experiences brief collisions, here we are dealing essentially with processes of multiple scattering -- with the principal role here being played by small-angle deflections, and this has as a result that trajectories must gradually change their direction (Figure 1). But nevertheless we can determine the values necessary in order to operate with plasma just as we operate with ordinary gas in elementary kinetic theory.

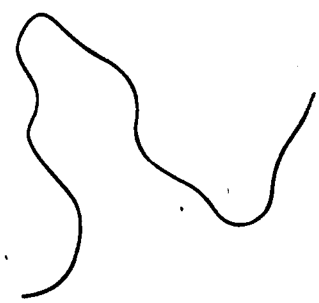

Figure 1. Trajectory of charged particle in plasma

In particular, effective cross section Q characterizing the processes of Coulomb collision can be written approximately thus:

$$Q = \frac{3 \cdot 10^{-5}}{T^2}\ cm^2,$$

where T is the temperature of the corresponding component in degrees.

Important here is the fact that the effective cross section of Coulomb interaction among particles of fully ionized plasma decreases very rapidly as temperature rises.

Gas without Collisions

At a temperature which is characteristic of the thermonuclear level, i. e. around one billion degrees, the effective Coulomb-collision cross section becomes a very small value of the order of 10^{-23} sq cm. Consequently in the processes which we ordinarily consider in studying the behavior of high-temperature plasma collisions cannot play a significant part. In a confined space high-temperature plasma can in many instances be regarded as a mixture of two gases in which collisions between particles do not take place.

Owing to the low magnitude of the effective collision cross section, plasma is of course a good conductor of electricity, its conductivity increasing rapidly with the increase of temperature, and at $T \sim$ one billion degrees the conductivity of hydrogen plasma should exceed the conductivity of a highly conductive metal (silver or copper) several hundred times. If the Wiedemann-Franz law holds true in this case, plasma should also be a very good heat conductor.

Such are the characteristic properties of high-temperature plasma as predicted by theory.

Naturally when we set ourselves the problem of producing this new state of matter, it is precisely these properties with which we have to reckon. It follows hence, in particular, that high-temperature plasma can be produced only provided it will occupy a certain limited space, without reacting over its entire surface with anything apart from a high vacuum. Obviously this can be effected only by means of strong magnetic fields. That is why the principal role in the physics of high-temperature plasma is played by the process of the plasma's interaction with strong magnetic fields. Lacking these, it is hopeless to try to create high-temperature plasma because only they are able to confine plasma within a certain region of space and heat it up without disastrous leakage of energy.

Thus, principal importance attaches to that division of modern plasma physics which studies the interaction between plasma and magnetic fields.

Plasma and Magnetic Field

Let us pass on to the general laws which characterize this interaction. Clearly, if we approach the question as to the properties of high-temperature plasma from a microscopic point of view, a magnetic field restricts the movement of charged particles, twisting the trajectory of each of them.

What is plasma from the macroscopic point of view? It is a diamagnetic gas which reduces magnetic field intensity in the space which it occupies. Created in conformity therewith is that difference in magnetic pressures $H^2/8\pi$, which confines the plasma in this space.

When we deal with strong lines of force parallel to one another, the pressure of plasma P can be said to equal the difference between magnetic pressures:

$$P = \frac{H_1^2}{8\pi} - \frac{H_2^2}{8\pi},$$

where H_1 and H_2 are magnetic field intensities outside and inside the plasma. In the more common case for plasma in a magnetic field, an equation of the following type can be written:

$$\rho a = -grad\left(P + \frac{H^2}{8\pi}\right),$$

where ρ is plasma density and a acceleration.

Actually this is Newton's second law applied to pressure $P + \frac{H^2}{8\pi}$.

Magnetic Traps

Here we must note that the most significant role during the early, initial stage of development of research on hot-plasma physics was played by studying the possible equilibrium configurations of plasma in a magnetic field.

Let us enumerate the most important equilibrium configurations of plasma. Let us start with systems that use the pinch effect. Here a magnetic field confining the plasma pressure is produced by a current flowing over the plasma itself under the influence of a voltage potential applied from the outside. There is a large group of systems of this kind which can be used to obtain and confine high-temperature plasma.

The number of so-called magnetic traps is very large. They are devices in which we "plunge" plasma into an external magnetic field and by means thereof confine it in a restricted region. Roughly speaking, they can be distributed over the following groups. To the first group belong the so-called open traps in which plasma is confined in a certain region of space with open magnetic-field lines of force. The second group includes traps of toroidal form with closed plasma pinches. This form may be distorted one way or another but it preserves its fundamental topological properties.

Let us have a brief look at what the open-type magnetic trap is. It is a system based on the fact that the motion of charged particles in a magnetic field is subject to a general law -- the principle of adiabatic invariance. It holds true if magnetic field intensity does not vary too sharply throughout the region here under study by us. Then during the movement of particles the quantity which is called the adiabatic invariant preserves a constant value:

$$\frac{W_1}{H} = \frac{Mv_{\perp}^2}{2H} = const.$$

Here W_1 is kinetic energy, and v_1 is circular velocity of transverse rotation. Thanks to this law, if a particle moves along the lines of force, when it enters the region of a more powerful field, its kinetic energy of transverse rotation increases in proportion to field intensity. And inasmuch as total kinetic energy in a magnetic field does not change, W_1 consequently reaches total kinetic energy, i. e. lengthwise motion ceases. Longitudinal velocity changes to zero and then changes its sign. Thus particles entering the region of a strong field rebound in the opposite direction.

This is the working principle of all open traps. The simplest trap of such type will be a system in which the magnetic lines of force have the structure shown in Figure 2.

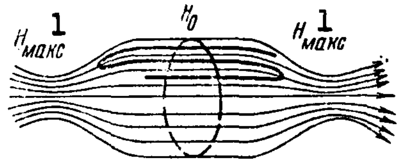

Figure 2. Field with magnetic mirrors

Key: 1. max

Such a field can be created by means of two coils conducting a current in one direction.

Such a trap was first suggested by A. M. Budker who called attention to the possibility of using the principle of adiabatic invariance to confine charged particles and plasma in systems of this type.

I want to note that not every particle is confined in such a field: the ones whose velocity is directed exactly along the line of force will slip out of it, but a considerable portion of the particles can be retained. That is why in high-temperature plasma we can disregard particle collisions; the particles can be kept for a long time in a magnetic trap until they collide with one another in such a way that their velocity vector is turned along the lines of force.

It is extremely easy to produce plasma in this group of systems. Therefore a considerable portion of the experimental and theoretical works has been devoted to analyzing the behavior of plasma therein.

I shall not dwell on closed systems. I want only to observe that their number includes the ingenious magnetic trap, called the "Stellarator," which has been studied for many years in the USA.

What Has Been Done Experimentally?

Even if we master the problem of the equilibrium confinement of plasma in a magnetic field, this will not mean that the problem is solved as we believed at an earlier stage of investigation. A new question arises: If plasma is in equilibrium, will this equilibrium be stable? The stability problem is the number-one problem in the present-day physics of high-temperature plasma. In particular, it is precisely upon how we are able to master it that the prospects of controlled thermonuclear synthesis depend.

Experimental research on the physics of high-temperature plasma was initiated in our country, in the USA and in England approximately in the 1950's -- each country of necessity having to act independently inasmuch as this research was conducted under the cloak of profound secrecy.

I should like to note two funny circumstances which are perhaps not so significant for this particular field as they are, rather, of a general character.

In the first place, a purely psychological factor. The fact that the cloak of secrecy existed and there was no one to follow who had gone ahead to pave the way in some measure stimulated initiative and independence in working out the problem. We were obliged to develop our own methods without looking to anybody else. This applies not only to us, but also to the Americans and Englishmen.

I must say that at the initial stage of work this absence of information was a beneficial, rather than an adverse factor. It was necessary in the same way that in a developing industry protective tariffs are necessary.

This does not mean that I am for the preservation of secrecy. Far from it! Sooner or later the mantle of secrecy has to be lifted from scientific work.

The second interesting circumstance is the experimental demonstration of the oneness of human thinking. When at the Second Geneva Conference results and ideas were compared for the first time, experimentation with high-temperature plasma was still at a low level. But curiously enough, the ideas were absolutely identical. Even the laboratory jargon was identical. Not only the general ideas, but even the concrete proposals had a practically identical character and had been advanced at almost the same time.

Let us pass on now to an exposition of experimental results. Here we shall be very brief because experimental research on plasma physics is still in a beginning state. I can tell about these results, relying mainly on our work in the Soviet Union since Soviet physics has had a worthy place in the work on these problems. The research under way in the USSR encompasses all the most important trends in the physics of high-temperature plasma.

The natural inception of this work was to study the simplest process: a strong pulse of current is passed through deuterium or other light matter which rapidly heats up. The current fulfills both the heating function and the function of confining the plasma by means of its proper magnetic field. The good thing about these experiments is that they require comparatively simple technique. One takes a porcelain or glass discharge tube and by means of the appropriate measuring apparatus observes what happens to rapidly-forming plasma in the space of several microseconds.

This work had as its result the successful production for the first time in the laboratory of plasma with a temperature of a million degrees and with a density of the order of 10^{15}-10^{16} particles per cubic centimeter.

The most interesting phenomenon discovered here was the appearance of hard radiation: when an electric potential of 5-10 kilovolts is applied to a tube, gamma rays originate with a considerably higher energy than that which corresponds to the applied electric potential.

During work with deuterium even neutron emission is observed. These hard radiations originate, as has been successfully shown, in the main not in consequence of thermonuclear reactions, but as a result of the processes of electromagnetic particle acceleration.

We must note yet another circumstance. In this process we can hold a high temperature for only a very brief interval of time, primarily because in such plasma the current pinch (Figure 3) proves to be unstable, as is every soft pinch. Here we encountered for the first time the instability phenomenon in plasma in the simplest form, in the form of instability of soft conductors that have no hardness -- the simplest type of magnetic instability. Ways of stabilizing plasma pinches had to be sought. And this led us to systems in which such instability, peculiar to strong currents, was eliminated.

As theoretical investigations have shown -- and theory has always led experimentation forward, the necessary conditions for this are created when an electric discharge appears in a very strong longitudinal magnetic field. If the intensity of the longitudinal magnetic field is very great, it becomes possible to overcome the most hazardous large-scale instabilities peculiar to plasma conductors. In case we want to produce the quasistationary conditions for heating up the plasma, we must switch from a direct conductor to a closed conductor, i. e. to systems of the toroidal type. Such systems are one of the fundamental research subjects in the present-day physics of high-temperature plasma.

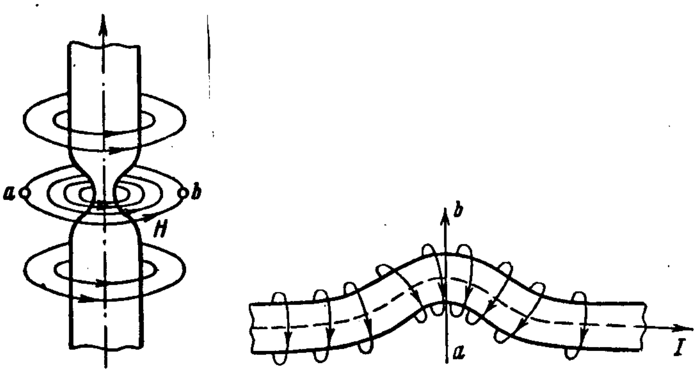

Figure 3. Simplest types of deformation that a plasma column can experience as a result of random fluctuations: local constriction of plasma pinch (at left); and wriggle of plasma pinch (at right).

Inside the chamber confining the plasma an electric current is created by induction, and by means of coils a longitudinal magnetic field which serves as an effective stabilizer of plasma instability (Figure 4).

In systems of this type we have been able completely to overcome large-scale plasma instability, just as theory had predicted.

However at present it is still impossible to say that such a pinch is completely stable. We cannot assert that there are not some small-scale instabilities which are hardly discernible on oscillograms, but which result in very rapid leakage of heat and particles. Only prolonged work will be able to demonstrate whether one can, by proceeding in this way, bring about total stabilization of the plasma pinch as far as all kinds of instability are concerned.

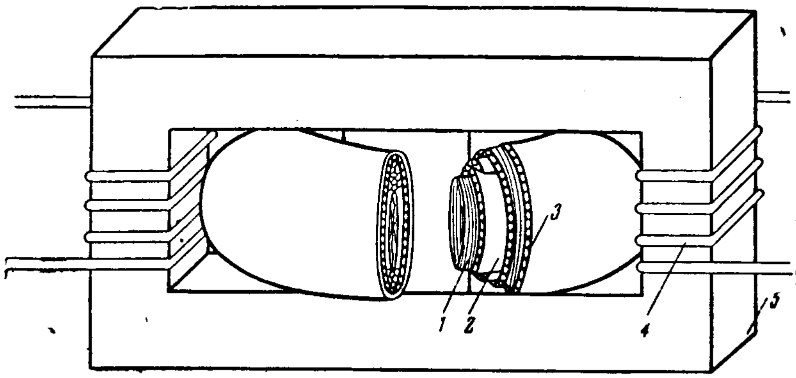

Figure 4. Diagram of toroidal discharge chamber with longitudinal magnetic field; internal chamber or liner (1), external copper chamber (2), winding that produces longitudinal magnetic field (3), primary transformer winding (the secondary winding is plasma turn) (4), iron core (5).

At present we have plasma pinches with a temperature (electronic and ionic) of several million degrees with a concentration of the order of 10^{13} particles per cubic centimeter and with plasma-particle confinement-time determined by cautious estimates to last for at least several milliseconds, i. e. it has been possible significantly to lengthen the "life-span" of particles in plasma.

All this applies to systems which have received the designation "Tokomak."

Experimenters paid the greatest attention to the problem of open magnetic traps. In particular, a great deal of work was devoted to very simple traps with magnetic mirrors. At present this work is under way on a large scale in our country, in the USA and in England. In our country, for example, the largest of all devices of this type is in operation and has been given the designation, "Ogra." At the present time "Ogra-2" has gone into operation. In the USA there are

"Alice" and "Scylla;" in England there is "Phoenix."

In systems of this type plasma can be obtained by various methods. In the first place, it is simply "collected fragment by fragment" from individual particles, i. e. particles are injected into a magnetic field. Further, plasma can be produced by injecting plasmoids from special magnetic guns and compressing them in a magnetic field. Use can be made of the so-called turbulent-heating method which has been successfully employed by Ye. K. Zavoyskiy in Moscow and by staff members of the Institute of Nuclear Physics in Novosibirsk.

Plasma Instability -- Detriment and Benefit

Plasma with hot electrons can be confined for many milliseconds but in all the cases that we know about from foreign literature plasma was successfully confined in a system with hot ions for only a few microseconds. Consequently, such a trap has an instability which is of an altogether natural character.

The magnetic field increases in a longitudinal direction but decreases in a transverse direction. Plasma is a diamagnetic. If any little tongue sticks out laterally from it, on entering a weaker field this tongue naturally protrudes further.

Can such instability be overcome within the scope of simple design? There are a number of investigations which show that stability can be assured if hot plasma is surrounded by a cloud of cold plasma. The extent to which this mechanism will be effective remains an open question at the present time.

The simplest way out of this situation is to increase the complexity of the geometry of the magnetic field somewhat and to switch from a system of the type considered above to magnetic fields that increase in all directions. Magnetic fields of this kind (they are called hybrid magnetic fields) were first tested by M. S. Ioffe and his associates at the Institute of Atomic Energy imeni I. V. Kurchatov [See Note] (Figure 5). For the commonest and simplest reasons the system has to be stable in this case. One can see here the clearcut transition from unstable to stable system.

[Note]: See Priroda (Nature), 1964, No. 2, p. 117.

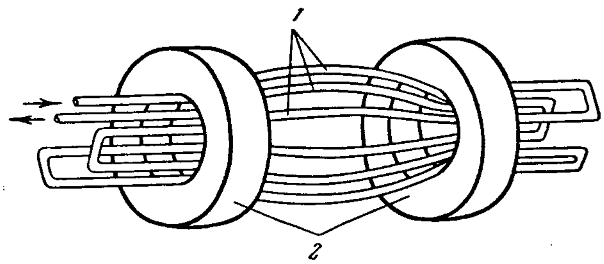

Figure 5. Diagram of trap with combined magnetic field: 1--supplemental conductors with current; 2 -- coils of basic magnetic field.

When these first experiments were published in 1963, they evoked extensive comment abroad. Now many American and English devices have been reconstructed according to the hybrid-field principle.

The experiments of M. S. Ioffe's group conclusively demonstrated that plasma can be stably confined in a restricted region but, to be sure, given a density which at present does not much exceed 10^{10} particles per cubic centimeter. It is not clear just what will happen at greater densities.

With every passing month theoretical analysis brings up new kinds of plasma instability in M. S. Ioffe's trap. Although the simplest kind of instability has been overcome, it does not follow that this will continue to be so since we are encountering a vast number of new types of instability associated with new types of resonant buildup of oscillations in magnetic systems, and it is very difficult to say whether with further increase of density it will be possible to skirt this tremendous mass of reefs. If we are able to get to a density level of 10^{13}-10^{14} particles per cubic centimeter, this will mean that we will overcome these difficulties satisfactorily.

What fundamental problems now confront us? For theory, of course, it is important to continue research on questions of stability, it being necessary to proceed from just establishing the appearance of instability to calculating the transfer coefficients that characterize heat conduction and diffusion in plasma, given various mechanisms whereby deviations from the stable state arise.

As for experimentation, the most important problem is to continue the investigation of plasma in magnetic traps -- primarily in such traps as assure the complete overcoming of the most hazardous large-scale instabilities of the magnetohydrodynamic type. In this connection plasma density must gradually be increased in order to see whether we will be able to penetrate the new barriers awaiting us.

Moreover, even if we are able to bring about stable plasma confinement, this does not mean that the problem of obtaining dense high-temperature plasma has been solved. We still need to have good heating methods.

We have already mentioned the new method for the turbulent heating of plasma, developed by Ye. K. Zavoyskiy and staff members at the Institute of Nuclear Physics of the Siberian Department of the Academy of Sciences USSR.

This method makes efficient use of the original, initial instability to heat the plasma. Then the instability comes to an end and in principle the plasma with which one can work further has to be produced. Thus, one not only has to combat instabilities, but must also use them under certain conditions in order to bring about the initial warming up of such a system.

Another problem is somewhat to the side. In our first experiments we found that unstable plasma serves as a source of fast particles. In all subsequent experiments researchers repeatedly came across these and sometimes took them as the result of the thermonuclear process. Actually, this was the result of the fact that unstable plasma continuously produces fast particles.

Characteristic of any -- albeit weakly turbulent -- plasma is the particle energy-spectrum depicted in Figure 6. Superimposed here on the usual Maxwellian distribution is a "hump," indicating the excess of fast particles. We encounter such a phenomenon in all experiments: if the plasma begins to "quiver" slightly, fast particles show up instantly. Evidently, analogous processes result in the origin of fast particles arriving here from the Sun's surface, as well as a certain portion of the cosmic rays. Thus the non-Maxwellian character of the spectrum is a specific peculiarity of of nonstationary plasma. It is difficult to say whether a general law exists to describe phenomena of this kind.

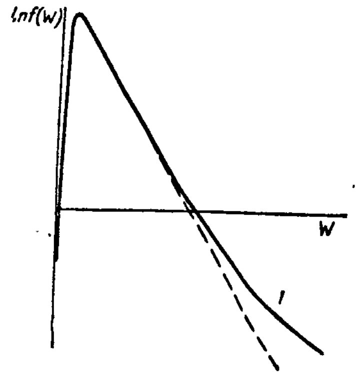

Figure 6. Energy spectrum of plasma particles. Shown along the axis of abscissas is energy W; along axis of ordinates the logarithm of the distribution function; shown by the broken line is Maxwellian distribution: 1 -- non-Maxwellian "tail" which is explained by processes of particle acceleration in plasma

But even if no general mechanism exists, one will always find the pertinent concrete mechanism of stochastic (probabilistic) dispersion in plasma waves of one type or another. Characteristic of all the known experiments is the fact that it is difficult to obtain plasma without an excess of fast particles.

* * *

What, now, are the prospects of thermonuclear synthesis?

It is hard to make precise predictions. One thing is clear, of course; a very great step forward has been made. Actually, in comparison with what we had about five to seven years ago, our prospects as of today are, let us say cautiously, far more favorable. Once the hybrid-field system had been created and plasma had been freed of elementary instability of the convective type, the road ahead lay open.

Therefore we can say that when the concrete need for thermonuclear energy appears, the problem will, obviously, be solved. But we must hope that we still have a margin of time.